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Probing the neutron star spin evolution in the young SMC Be/X-ray binary SXP 1062

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ABSTRACT
The newly discovered Be/X-ray binary in the Small Magellanic Cloud, SXP 1062, provides the first example of a robust association with a supernova remnant (SNR). The short age estimated for the SNR qualifies SXP 1062 as the youngest known source in its class, $\tau \approx 10^4$ yr. As such, it allows to test current models of magneto-rotational evolution of neutron stars in a still unexplored regime. Here we discuss possible evolutionary scenarios for SXP 1062 in the attempt to reconcile its long spin period, $P = 1062$ s, and short age. Although several options can be considered, like an anomalously long initial period or the presence of a fossil disc, our results indicate that SXP 1062 may host a neutron star born with a large initial magnetic field, typically in excess of $\sim 10^{14}$ G, which then decayed to $\sim 10^{13}$ G.

Key words: stars: neutron – X-rays: binaries: SXP 1062.

1 INTRODUCTION

Be/X-ray binaries (or BeXBs for short) form a subclass of the high-mass X-ray binaries (HMXBs) in which the neutron star (NS) companion is a Be star, a spectral class B giant/subgiant with emission lines and large IR flux. These peculiar properties are explained in terms of an equatorial disc, formed by matter lost by the rapidly rotating Be star. X-ray emission is believed to be powered by accretion of material in the equatorial disc onto the NS (see e.g. Reig 2011, for a recent review).

BeXBs are both transient and persistent X-ray sources. Transient systems are characterized by type I-II outbursts during which their flux increases by a factor 10–10^4 over the quiescent level. They typically contain a not-too-slow NS ($P \lesssim 100\,$s) on a moderately eccentric orbit, $P_{orb} \lesssim 100\,$d, $e \gtrsim 0.2$. On the other hand, persistent BeXBs exhibit a rather flat lightcurve, lower X-ray luminosity ($L \approx 10^{34}$–10^{35} erg s^{-1}), longer spin and orbital periods ($P \gtrsim 200\,$s, $P_{orb} \gtrsim 200\,$d; see again Reig 2011).

There are presently about 30 well-established BeXBs in the Galaxy, plus ~ 40 candidates. In addition, ~ 50 sources (plus ~ 20 candidates) are known in the Small Magellanic Cloud (SMC)[1]. Very recently Hénault-Brunet et al. (2012) reported the discovery of a new BeXB in the Wing of the SMC. The new source (SXP 1062) has the typical properties of a persistent BeXB: a B0-0.5(III)e+ donor, $L \sim 6 \times 10^{35}$ erg s^{-1}, $P \sim 1062\,$s, and an orbital period $P_{orb} \sim 300\,$d, as estimated from the Corbet diagram (Corbet et al. 2009). What makes SXP 1062 to stand out amongst its kinship is its (likely) association with a supernova remnant (SNR). BeXB-SNR associations have been already reported (again in the SMC) but in all previous cases they appear uncertain (Hughes & Smith 1994; Coe, Haigh & Reig 2000). In the case of SXP 1062 the association looks robust and allows for the first time to estimate the NS age in a BeXB from that of the parent SNR, $\tau \sim 2$–4×10^4 yr (Hénault-Brunet et al. 2012). The suggested association of SXP 1062 with a SNR has been further strengthened by a reanalysis of the same *XMM-Newton* datasets, supplemented with optical and radio observations, by Haberl et al. (2012). Their estimate for the SNR age, 1.6×10^4 yr, is even shorter than, albeit fully compatible with, that of Hénault-Brunet et al. (2012). Haberl et al. (2012) were also able to measure the source period evolution, which results in a positive (i.e. spin-down) rate $\dot{P} \sim 3 \times 10^{-6}\,$s s$^{-1} \sim 95\,$s yr^{-1}.

The long spin periods ($P \gtrsim 1000\,$s) of some persistent BeXBs have been for a long time a major issue. According to the standard picture, there are four stages in the spin evolution of a neutron star embedded in a medium: ejector, propeller, accretor and georotator[2] (e.g. Lipunov 1992). Once the NS entered the accretor stage after a short propeller phase, its spin period quickly settles at an equilibrium value, P_{eq}. In the conventional model, based

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[1] Figures from Reig (2011) and the BeXB online catalogue at http://xray.sai.msu.ru/~ raguzova/BeXcat; see also Raguzova & Popov (2005).
[2] The last one is of no concern here, since it occurs under specific conditions, hardly met in HMXBs.

on Davies & Pringle (1981) results, the star dipole field should be $B \gtrsim 10^{14}$ G to have $P_{eq} > 10^3$ s, unless the accretion rate is orders of magnitude below what needed to account for the observed X-ray luminosity. Since observations support the presence of a NS with standard magnetic field (at least in some BeXBs), the subsonic propeller stage, which can delay the onset of accretion until a much longer period is reached (Ikhsanov 2007), has been invoked to explain ultra-slow BeXBs (see Reig 2011). More recent investigations of wind-fed accretion onto magnetized NSs indicate, however, that the equilibrium period can be as high as $\sim 1000\,\mathrm{s}$ even for $B \approx 10^{12}$–10^{13} G and $\dot{M} \approx 10^{16}\,\mathrm{g\,s^{-1}}$, as expected in BeXBs (Shakura et al. 2012).

Whatever the details of the braking torques, the previous argument implicitly relies on the assumption that the present age of the source is long enough for the NS to have entered the propeller stage. Unless the accretion rate is way above typical, a NS in a BeXB with $B \gtrsim 10^{12}$ G starts its evolution in the ejector (or pulsar) phase. Its duration can be roughly estimated as $\tau_{ej} \gtrsim 10^6 (B/10^{12}\,\mathrm{G})^{-1} (\dot{M}/10^{15}\,\mathrm{g\,s^{-1}})^{-1/2}$ yr (see Section 2). This is comfortably below (by a factor ≈ 10) the lifetime of the Be companion, so there is ample room for the binary to start an accretion-powered X-ray stage. In the case of SXP 1062, however, it would be impossible for the NS to enter the propeller stage (and hence to become an accretor) in a time as short as a few $\times 10^4$ yr, the estimated SNR age, for typical values of B and $\dot{M}$. The accretion rate in SXP 1062 is $\dot{M} = L/\eta c^2 \sim 6 \times 10^{15}\,\mathrm{g\,s^{-1}}$ for an efficiency $\eta = 0.1$, so this points to a highly magnetized NS, with an initial magnetic field substantially above 10^{12} G.

2 SPIN EVOLUTION IN SXP 1062

2.1 Spin-down torques

In the standard picture of NS spin evolution (see e.g. Lipunov 1992), the transitions among the different stages are regulated by the relative values of some characteristic radii. In the ejector phase the light cylinder radius, $R_l = cP/2\pi \sim 5 \times 10^9\, P\,\mathrm{cm}$, is typically smaller than the gravitational capture radius, $R_G = 2GM/V^2 \sim 4 \times 10^{11}\, V_{300}^{-2}\,\mathrm{cm}$, where V is the velocity (and ρ the density) of matter far from the star[3]. A NS with $M_{NS} = 1.4\, M_\odot$, $R_{NS} = 10\,\mathrm{km}$ and moment of inertia $I = 10^{45}\,\mathrm{g\,cm^2}$ is assumed henceforth. The transition to the propeller stage occurs when the ram pressure, $P_{dyn} = \rho V^2/2$, balances the outgoing flux of electromagnetic waves and relativistic particles, $P_{PSR} = \dot{E}/(4\pi R^2 c)$, at R_G ($\dot{E}$ is the rotational energy loss rate of the pulsar). Once matter crosses R_G it is gravitationally captured and quickly reaches the light cylinder radius switching off pulsar emission, since the dynamical pressure (assuming a nearly spherical flow) rises as $R^{-5/2}$, while the relativistic momentum flux goes like R^{-2}.

The critical period for the transition follows by requiring that $P_{dyn}(R_G) = P_{PSR}(R_G)$ together with the standard expression for magneto-dipole losses, $\dot{E} = 8\pi^4 B^2 R_{NS}^6 \sin^2\alpha/(3c^3P^4)$ and mass conservation, $4\pi R_G^2 \rho V = \dot{M}$,

$$P_{ej} = 2\pi \left(\frac{4}{3}\frac{B^2 R_{NS}^6}{\dot{M} V c^4}\right)^{1/4} \sim 0.31\, V_{300}^{-1/4} \dot{M}_{16}^{-1/4} B_{12}^{1/2}\,\mathrm{s}; \quad (1)$$

[3] Hereafter $V_{300} \equiv (V/300\,\mathrm{km\,s^{-1}})$, $P_{orb\,300} \equiv (P_{orb}/300\,\mathrm{d})$, $P_{1000} \equiv (P/1000\,\mathrm{s})$ and N_X is used for the quantity N in units of 10^X cgs.

since the NS is not accreting, here $\dot{M}$ is more properly defined as the matter flow rate in the surrounding medium and we assumed a nearly orthogonal rotator ($\sin\alpha \sim 1$). From the magneto-dipole formula, assuming constant B and very short initial period, the time it takes the NS to spin down to P_{ej}, i.e. the duration of the ejector stage, can be evaluated

$$\tau_{ej} = \frac{3Ic^3 P_{ej}^2}{16\pi^2 B^2 R_{NS}^6} \sim 1.5\, \dot{M}_{16}^{-1/2} V_{300}^{-1/2} B_{12}^{-1}\,\mathrm{Myr}. \quad (2)$$

The dipole field in a wind-fed NS has been estimated by Shakura et al. (2012) under the assumption that the star is spinning at the equilibrium period (see also Postnov et al. 2011),

$$B_{12} \sim 8.1\, \dot{M}_{16}^{1/3} V_{300}^{-11/3} \left(\frac{P_{1000}}{P_{orb\,300}}\right)^{11/12}. \quad (3)$$

The previous expressions give $\tau_{ej} \sim 0.2\,\mathrm{Myr}$ for SXP 1062, about an order of magnitude larger than the estimated SNR age. Our reference value, $V \sim 300\,\mathrm{km\,s^{-1}}$, is a conservative estimate for the typical velocity of matter ejected from hot stars in binaries (see Raguzova & Lipunov 1998). Actually, since Eq. (3) depends rather strongly on V, higher velocities would result in a lower magnetic field and longer τ_{ej}.

Within this framework, an obvious possibility to shorten the ejector phase in SXP 1062 is to invoke a higher dipole field. However, if the present field is that given by Eq. (3) this implies that B must have been stronger in the past and then decayed to its present value. The issue of magnetic field evolution in isolated NSs and its observable consequences has been recently addressed in detail, especially in connection with strongly magnetized objects, or magnetars (e.g. Pons, Miralles & Geppert 2009; Popov et al. 2010; Turolla et al. 2011, and references therein). In these studies it is assumed that magnetic field decay takes place in the stellar crust and is driven by Hall/Ohmic diffusion. Both processes are strongly density- and temperature- dependent, so magnetic and thermal evolution are necessary coupled, and a multidimensional numerical approach is needed (Pons, Miralles & Geppert 2009).

Since we are interested in tracing the spin evolution of SXP 1062 prior it entered the accretor stage, we can treat the NS as isolated for the sake of magnetic evolution. In order to avoid complex numerical simulations, we adopt the simplified approach of Aguilera et al. (2008) in which the dipole magnetic field decay is described by the analytical law

$$B(t) = \frac{B_0 \exp(-t/\tau_O)}{1 + (\tau_O/\tau_H)[1 - \exp(-t/\tau_O)]} + B_{fin}, \quad (4)$$

where B_0 is the initial field, B_{fin} is the relic field, τ_O and τ_H are the characteristic timescales of Ohmic and Hall decay, respectively. The period evolution in the ejector stage is given by the (generalized) magneto-dipole formula

$$\dot{P} = \frac{8\pi^2 B^2 R_{NS}^6 (1 + \sin^2\alpha)}{3Ic^3 P} \quad (5)$$

(Spitkovsky 2006), where B is given by Eq. (4).

The NS enters the propeller phase as soon as the dynamical pressure exerted by the incoming material overwhelms the pulsar momentum flux at the gravitational radius, as discussed above. If no stable equilibrium exists, matter will reach the light cylinder radius on a free-fall timescale, and proceed inwards if the ram pressure overcomes the magnetic pressure of the dipole field, $P_{mag} =$

$B^2/8\pi$. Ekşi & Alpar (2005) have shown that stable matter configurations can be present even if the inner boundary of the flow, R_{in}, is outside R_l. This occurs when $R_{in} < R_{crit} = F(\alpha)R_A$, with $F(\alpha) \geqslant 1$ a function of the magnetic tilt angle and[4] $R_A = (1/2)B^{4/7}R_{NS}^{12/7}/(8GM_{NS}\dot{M}^2)^{1/7}$. For $R_l < R_{in} < R_{crit}$, the pulsar is still active and the star is spun down by magneto-dipole torque. Under these conditions Ekşi & Alpar (2005) provide an expression for R_{in} in terms of α and R_A. When $R_{in} < R_l$, instead, the flow is truncated at the Alfvén radius, where $P_{dyn} = P_{mag}$, the pulsar is turned off and only propeller torques act.

The propeller physics is very complicated and no unanimous consensus exists about the form of the torque. However, since spin-down is expected to be very efficient in the propeller phase, its duration is quite short. The period rapidly increases and the corotation radius, $R_{co} = [GM_{NS}/(4\pi^2)]^{1/3}P^{2/3}$, moves quickly outwards until it matches the Alfvén radius, at which point accretion begins and the period freezes at the equilibrium value. While the latter depends on the propeller/accretion mechanisms, and several options have been discussed (see Sec. 1), the duration of the ejector phase does not. For this reason we consider here only the "maximally efficient torque" (see e.g. Francischelli & Wijers 2002), as an illustrative example:

$$\dot{P} = -\dot{M}R_{in}^2\left[\Omega_K(R_{in}) - 2\pi/P\right]\frac{P^2}{\pi I} \qquad (6)$$

where Ω_K is the keplerian angular velocity.

Finally, to follow the period evolution in the accretor stage, $R_{in} < R_{co}$, we assume the settling accretion regime recently proposed by Shakura et al. (2012, see also Postnov et al. 2011)

$$\dot{P} = -\left[A\dot{M}_{16}^{(3+2n)/11} - C\dot{M}_{16}^{3/11}\right]\frac{P^2}{2\pi I}. \qquad (7)$$

Here $A \sim 2.2\times10^{32}K_1(B_{12}R_{NS\,6})^{1/11}V_{300}^{-4}P_{orb\,300}^{-1}$, $C \sim 5.4\times10^{31}K_1(B_{12}R_{NS\,6})^{13/11}P_{1000}^{-1}$ (both in cgs units); the constant K_1 and the index n were fixed to 40 and 2, respectively. The accretion torque can produce either spin-up or spin-down and it is interesting to note that in the spin-down phase P increases exponentially, with a typical timescale $\approx 100B_{12}^{-13/11}\dot{M}_{16}^{-3/11}$ yr.

2.2 Results

We solved numerically the equation for the period evolution in the three stages (Eqs. [5], [6], [7]) starting from $t_0 = 0.01$ yr with an initial period $P_0 = 0.01$ s. The accretion rate was fixed to the value derived from current observations, $\dot{M} = 6\times10^{15}$ g/s, together with $P_{orb} = 300$ d, $V = 300\,\mathrm{km\,s^{-1}}$, $\tau_O = 10^6$ yr and $B_{fin} = 8\times10^{12}$ G. Several cases were then computed varying the magnetic dipole angle α, the Hall timescale τ_H and especially the initial field B_0. Figure 1 illustrates the results for $\alpha = 10^\circ$, $\tau_H = 10^3$ yr and $B_0 = 4\times10^{14}, 10^{14}, 7\times10^{13}, 4\times10^{13}, 10^{13}$ G. A common feature to all evolutionary tracks is a very rapid propeller stage which is followed by an even more rapid spin-down phase as the NS enters the accretion regime. The period then saturates at its equilibrium value. The decrease in P seen at later times for the larger fields is due to the dependence of P_{eq} on B and to the fact that the field is still decaying (see Sec. 2.1). The time variation of B is also responsible for the deviations of $P(t)$ from a power-law in the later ejector phase, which are, again, more prominent for large B.

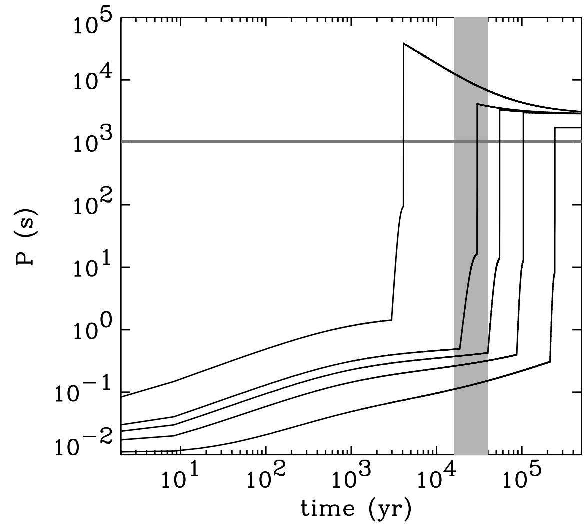

Figure 1. The spin period evolution for $\alpha = 10^\circ$, $\tau_H = 10^3$ yr and $B_0 = 4\times10^{14}$, 10^{14}, 7×10^{13}, 4×10^{13}, 10^{13} G (solid lines, from top to bottom). The shaded areas mark the age (vertical strip) and period (horizontal strip) of SXP 1062 with the respective uncertainties.

The main information Figure 1 conveys is that a quite large initial field is required in order for SXP 1062 to enter the propeller phase (and quickly start accreting) in a time as short as a few $\times10^4$ yr. For the case shown here it has to be $B_0 \gtrsim 10^{14}$ G for this to occur. This result is not very sensitive to the actual choice of α and τ_H. Both increasing α and decreasing τ_H results in a somehow higher value of the minimum initial field, which is however in all cases in the range $\sim 10^{14}-4\times10^{14}$ G. The conclusion that SXP 1062 harbours an initially strongly magnetized NS seems therefore quite robust.

We stress that our main goal is not to reproduce within the current model the observed value of P at the present age. Although, for completeness, we followed the spin evolution also in the propeller and accretor stages, the treatment we employed is necessary approximated and contains some degrees of arbitrariness in the choice of the propeller/accretor torques. Our computed evolution past the ejector phase has mainly an illustrative purpose and has to be taken with caution.

3 DISCUSSION

The quite short age implied by the association of the newly discovered BeXB in the SMC SXP 1062 with a SNR (Hénault-Brunet et al. 2012; Haberl et al. 2012) raises a number of questions about the properties of the neutron star and its evolutionary status. Normally, one expects that accreting X-ray pulsars spin close to their equilibrium period. However, for a such a young system this appears far from granted. Haberl et al. (2012) reported a large spin-down rate for SXP 1062, which may suggest that P_{eq} has not been reached yet. According to the standard evolutionary scenario (Lipunov 1992), the (maximum) spin-down rate in the accretor stage is $\dot{P} \sim 2\pi B^2R_{NS}^6/(GMI)$ which implies $B \approx 3\times10^{14}$ G for $\dot{P} \approx 100\,\mathrm{s\,yr^{-1}}$. On the other hand, if Eq.

[4] Although R_A formally coincides with the Alfvén radius, we remark that the latter exists only inside the light cylinder radius. Nonetheless, the present definition is correct, provided that R_A is not associated to the equilibrium of dynamical and magnetic pressure.

(7) is used to estimate the magnetic field, a much lower value is obtained, $B \approx 10^{13}$ G, very close to what is predicted assuming that the source spins at the equilibrium period (see Eq. [3]). This supports a picture in which the NS actually rotates close to P_{eq}. A further argument in favor of this is the very short duration of the spin-down phase in the accretor stage, $P/\dot{P} \lesssim 100\,\mathrm{yr}$, which makes it very unlikely to catch the source in this state. Our conclusion is that both the young age and the large spin-down rate of SXP 1062 argue in favor of an initially highly magnetic NS which experienced field decay.

Details of evolution past the ejector stage are uncertain, so a fine tuning of the model discussed in Sec. 2 is entirely premature. Still, some general considerations can be made. The main one is that the timescale required for reaching P_{eq} after the NS left the ejector stage is very short. A further point to be stressed is that the zero, or negative, period derivative at $P = P_{eq}$ (see Figure 1) does not account for variations in $\dot{M}$ due to orbital motion in the BeXB and irregularities in the wind. This can result in quite large values of $\dot{P}$ and rapid changes in the period derivative which are indeed measured in wind-fed X-ray binaries (see e.g. Bildstein et al. 1997). In this respect the spin-down rate in SXP 1062 is large but not exceptionally so. For example, GX 301-2 is known to have a larger value of $\dot{P}$ (Koh et al. 1997). Haberl et al. (2012) measured the average period derivative over a time-span less than a month, $\sim$ one tenth of the orbital period. Fluctuations in $\dot{P}$ can occur on a timescale of days, so a more complete dataset is definitely needed to assess the real nature of the period variation.

Alternative scenarios to explain the long period and short age of SXP 1062 can be envisaged. For instance, Haberl et al. (2012) suggested that the NS could have been born with an initial period much longer than $\sim 0.01\,\mathrm{s}$. The value of P_0 can be evaluated by requiring that the transition period given by Eq. (1) is reached in less than the source age, and it turns out to be $\sim 1\,\mathrm{s}$ for the B-field corresponding to P_{eq} [Eq. (3)]. If this is the case no field decay is required. Although possible, no compelling observational evidence for such long initial periods in NSs exists. There are hints that some central compact objects (CCOs) in SNRs may have a current period very close to the initial one, $P_0 \approx 0.1\,\mathrm{s}$. These sources, however, are suspected to host weakly magnetized NSs ($B \approx 10^{11}$ G; e.g. Gotthelf & Halpern 2010). Whether the low field and the long period are related, depending on the conditions under which the NS formed, is still unclear. Still, the estimated value of B in SXP 1062 is much higher and the initial period required in the present case is more than one order of magnitude longer. Very recently Knigge, Coe & Podsiadlowski (2012) presented evidence that the population of BeBXs is bimodal, with the two sub-populations having distinct typical spin and orbital periods, and eccentricities. They suggest that the NSs in the two groups are produced through different channels, iron-core-collapse and electron capture supernovae, with the long spin period sources associated to the former channel. Whether this may result in a population of long P_0 NSs is a still open question.

Another possibility is that the NS in SXP 1062 could, at least in the early stages following its formation, have been surrounded by a debris (or fossil) disc, left by the parent supernova explosion. The existence of such a disc could also lead to rapid spin-down and large period. This, in addition to a super-strong field, was suggested to explain the ultra-long period ($\sim 6.67\,\mathrm{hr}$) in the enigmatic source RCW 103 (De Luca et al. 2006; Li 2007). Although this remains a possibility worth of further investigations, preliminary calculations, based on the model by Li (2007, see also Esposito et al. 2011), indicate that a large initial field ($B \gtrsim 10^{14}$ G) is still required, unless the disc is quite massive. For $M_{disc}(0) \sim 10^{-2}\,M_{\odot}$, the NS can enter the propeller stage earlier than $\sim 10^4$ yr also for $B \sim 10^{13}$ G.

If SXP 1062 indeed contains an initially strongly magnetized neutron star, then studies of this system can shed light on the origin of magnetars. In the standard scenario (Duncan & Thompson 1992) super-strong fields are generated via dynamo processes. This requires rapid rotation of the proto neutron star. Primary components in high-mass binary systems are not expected to form rapidly rotating cores at the end of their lives (Popov & Prokhorov 2006; Bogomazov & Popov 2009). Up to now no strongly magnetized compact objects have been identified in binary systems with certainty. Chashkina & Popov (2012) have recently derived estimates of the B-field in HMXBs using Shakura et al. (2012) formula and no evidence of ultra-high fields was found. It has been suggested that supergiant fast X-ray transients (SFXTs, see e.g. Sidoli 2011, for a review) may host a magnetar (Bozzo, Falanga & Stella 2008). More recently, Torres et al. (2012) reported magnetar-like behaviour from the peculiar binary LS I +61 303. However, no definite confirmation has been given yet, and, in this respect, SXP 1062 may be a unique example. The existence of a (evolved) magnetar in a high-mass binary system will pose new challenges on the origin of such neutron stars.

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